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A NEW ROBOT FOR HIGH DEXTERITY MICROSURGERY

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ABSTRACT

Drawing on our prior NASA work in high-fidelity teleoperation/telepresence, we are developing a new robotic system applicable to micro- and minimally invasive surgeries. The goal product is a dexterity-enhancing master-slave telerobot and controls that will refine the scale of current microsurgeries, and minimize effects of the involuntary tremor and jerk in surgeons' hands. As a result, exciting new surgeries of the eye, ear, brain and other critical faculties should become possible, and the positive outcome rates in conventional procedures will improve. In its nominal configuration, this new *Robot Assisted MicroSurgery* (RAMS) system has a surgeon's hand controller immediately adjacent to the robot. The RAMS system is also potentially applicable to "telesurgery" -- surgeries to be carried out in local-remote settings and time-delayed operating theaters -- as considered important in field emergencies and displaced expertise scenarios. As of August, 1994, we have developed and demonstrated a new 6 degree-of-freedom robot (slave) for the RAMS system, The robot and its associated Cartesian controls enable relative positioning of surgical tools to approximately 25 microns within a non-indexed and singularity-free work volume of ~20 cubic centimeters. This implies the capability to down-scale hand motion inputs by two to three times, and the consequent performance of delicate procedures in such areas as vitreo-retinal surgery, for which clinical trials of this robot are planned in 1996. Further, by virtue of an innovative drive actuation, the robot can sustain full extent loads up to three pounds, making it applicable to both fine manipulation of microsurgical tools and also the dexterous handling of larger powered devices of minimally invasive surgery. In this paper, we overview the robot mechanical design and controls implementation, and we summarize our preliminary experimentation with same. Our accompanying oral presentation includes a five minute videotape display of some engineering laboratory results achieved to date.

INTRODUCTION

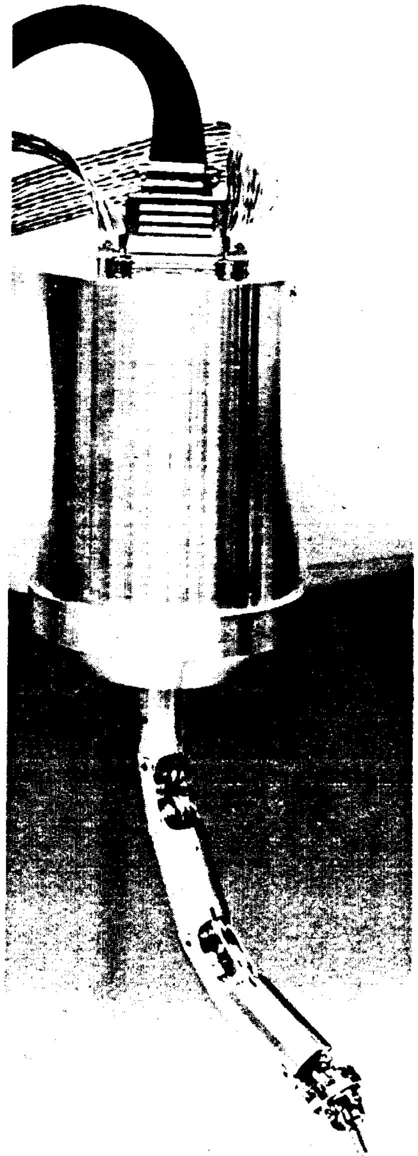
Medical applications of robotics are beginning to attract significant interest of both researchers and commerce. Several different application thrusts are being aggressively explored, as reported in recent special interest meetings and workshops [1 -4]. These thrusts include robot-assisted stereotaxic interventions (imaging-guided biopsy), orthopedic preparations by robot (precision joint emplacements), endoscopic & laparoscopic assists (minimally invasive procedures), teleoperative remote surgeries ("telesurgery"), and recently, robotically-enhanced microsurgery (high dexterity, scaled operations under microscopic viewing), Our primary interest is the last area, its connections to precision imaging guided surgical interventions -- and possibly later, telesurgeries. Building cm our prior NASA-JPL work in dexterous teleoperations and telerobotics at conventional scale, wc have begun development of a robotic micro-dexterity platform with potent i all y important ncw medical applications. This Robot *Assisted MicroSurgery* (RAMS) workstation targets ncw and improved procedures of the eye, ear, brain, nose, throat, face, and hand, The resulting technology developments are planned for evaluation in clinical microsurgery procedures circa 1996 -- we are working to this end in engineering collaboration with MicroDexterity Systems, Inc. (Chief Officer, Steven T. Charles, M.D.), under a NASA Technology Cooperation Agreement, with the goal that successful technology developments be commercialized.

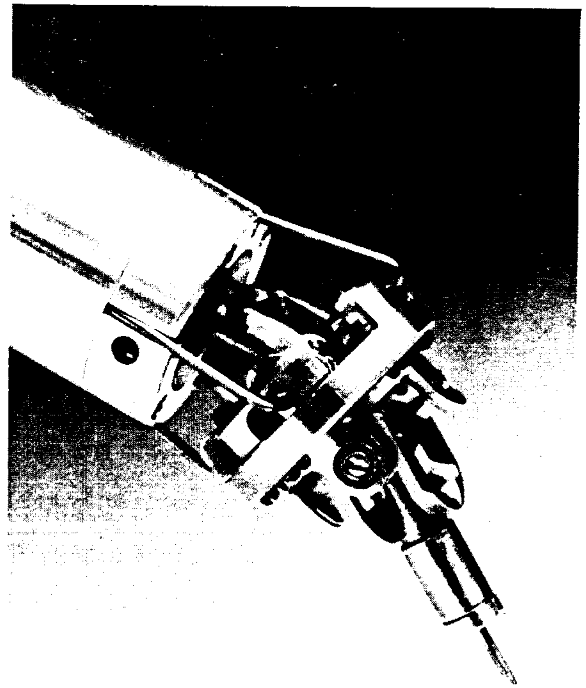
The RAMS workstation is conceived as a dual-arm 6-d.o. f. master-slave telemanipulator with programmable controls, onc arm handling primary surgical tooling and the other as auxiliary (suction, cauterization, imaging, etc.). The primary control mode is to be teleoperation, including task-frame referenced manual force feedback and possibly a cross-modal textural presentation. Later sensor-related developments include *in situ* imaging modes for tissue. feature visualization and discrimination. The operator will also be able to interactively designate or "share" automated control of robot trajectories, as appropriate. RAMS is intended to refine the physical scale of manual microsurgical procedures, while also enabling more positive outcomes for the average surgeon during typical procedures -- e.g., the RAMS workstation controls include features to enhance the surgeon's manual positioning and tracking in the face of the 5-101 Iz band myoclonic jerk and involuntary tremor that limit many surgeons' fine-motion skills. The first RAMS development, now completed and undergoing engineering evaluation, is a small six-d.o.f. surgical robot ("slave"), the configuration of which is a torso-shoulder-c]tmw (t/s/c) body with non-intersecting 3-axis wrist. This robot manipulator is approximately 25 cm. full-extent and 2.5 cm. in diameter. Robot actuation is based on a new revolute joint and cable-drive mechanism that achieves near zero backlash, constant cable length excursions, and minimized joint coupling. The robot design and controls currently allow non-indexed relative positioning of tools to within 25 microns and a work volume of -20 cm^3 -- a resolution some two or three times better than that typically observed in the most highly skilled microsurgeries.

ROBOT MECHANICAL DESIGN

Wc describe the robot design in this section, briefly outlining related design requirements, as motivated both by kinematic control objectives and robot suitability to re-usable and safe application in a sterile medical environment. **Figure 1** highlights some recent robot mechanical developments, e.g., the integrated six-d.o.f. robot slave (manipulator and nmtc)r-drive base), a 3-d.o.f. wrist (close-Llp view), and the highly novel double-jointed tendon drive rotary joint mechanization used in shoulder-and-clhow actuation. Figure 1 also lists at page-right some key robot features, as furt hcr elaborated below. The general model for the present at ion that follows is: wc list a design objective (*in italics*) and its definition; we then provide a brief technical description of the technical approach wc took to meet the objective. Where appropriate, and known to date, we give quantitative information.

*Figure I : Robot Assisted MicroSurgery (RAMS) **system six-d.o.f.** robot slave (manipulator and motor-drive base), **3-d.o.f.** wrist, and double-jointed tendon drive rotary joint*





Kev Features

- 6-d.o.f. serial arm (t/s/e+ 3-axis wrist)
- Torso can roll 165 degrees
- Shoulder/elbow rotate a full 360°
- Singularity-free wrist design
- Wrist pitch/yaw=1 80°, roll=540°
- Arm-wrist: L=25 cm, OD=2.5 cm
- Base: 12 cm OD, 17.75 cm long
- Weight (incl. base/motors): 5.5 lb.
- .25 cm center pass-through
- Quick-disconnect drive (sterilization)
- Cable-driven, decoupled joints
- Zero-backlash in five joints
- Low-stiction, custom bearing drive
- Stiffness ~15 lb./in at tip
- Full-extent arm force limit ~ 3 lb.
- Designed for 10µ positioning
- Commercially-vended electronics
- PLD based-control, power/braking
- Optically-isolated control interface
- Watchdog timer on processors

Mechanical Design

1. Drive Unit Separability: Autoclaving of the robot is possible by removing the motor/encoder units at the base prior to sterilization. The motor/encoder units can be re-attached in a quick and simple procedure.

This is done by integrating the motors/encoders into two distinct sets of three on a common mount and registering these packages via alignment pins. The resulting Iwo motor packages can be easily removed by undoing two screws and one connector on each set. The mechanism can then be autoclaved. The two motor' packages can be reinstalled quickly by reversing the removal procedure.]n normal operation the motors arc contained inside the robot's base, protecting anything they may contaminate. An added advantage obtained with this design is that debugging of servo- and kinematics control systems can be done while the motors arc not attached to the robot, thereby sparing the robot damage during software development and validation.

2. *Zero/Low Backlash: Low* backlash (free play) is essential for doing fine manipulation, especially since the position sensors arc on the motor shafts.

Five of the robot's six degrees of freedorn have zero backlash and the sixth has about 20 microns. Zero backlash is achieved by using dual drive-trains that are pre-loaded relative to onc another. These dual drive-trains arc coupled together at only the motor shaft and the joint output. The steel cables which actuate each joint also act as springs to pre-load the gear-train. The drive-train's pre-load can be easily adjusted by disengaging the motor, counter-rotating the dual drives until the desired pre-load is reached, and re-engaging the motor. This also allows for easy cable adjustment as the cables stretch with time.. The one axis that does not have zero backlash is a result of the wrist design which makes low backlash possible but zero backlash difficult, especially if stiction is a concern as with this robot.

3. Low *Stiction*: Stiction (stick/slip characteristic) must be minimized to achieve small incremental movements wit bout overshooting or instabi lit y.

Stiction was minimized by incorporating precision ball bearings in every rotating location of the robot (pulleys, shafts, joint axes, etc.), so as to eliminate metal-to-metal sliding. Due to Severe size and loading constraints, some of these bearings had to be custom dc.signed. (Indeed, there is only onc location in the wrist where such direct contact exists, because size constraints therein restricted usc of bearings. in this location, backlash was allowed to reduce stiction -- scc item 2.)

4. Decoupled *Joints*: Having all joints mechanicall y decoupled simplifies kinematics computations as wc]] as provides for partial functionality should one joint fail.

Developing a six axis, tendon-driven robot that has a]] joints mechanically decoupled is very difficult. Decoupling requires driving any given joint without affecting any other joint. The shoulder and elbow joints incorporate a unique double-jointed scheme that allows passage of any number of activation cables completely decoupled from these joints. The three axis wrist is based on a concept (as originated by Mark Rosheim) that not only decouples the joints, but also has no singularities. Further, he torso simply rotates the entire robot base to eliminate coupling. *If any one of the joints were to fail mechanically, the remaining five would be unaffected.*

S. *Large Work Envelope*: A large work volume is desirable so that the am's base will not have to be repositioned frequently during tasks.

To achieve a large work envelope, each joint needs to have a large range of motion. The torso was designed with 165 degrees of motion while both the shoulder and elbow have a full 360 degrees. This high range of motion in the shoulder and elbow is attained by the unique double-jointed scheme mentioned above. The wrist design (utilizing the Rosheim concept) has 180 degrees of pitch and yaw with 540 degrees of roll. Such large motion ranges greatly reduce the chance of a joint reaching a limit during operation, thus increasing the work volume.

6. *High Stiffness*: A stiff manipulator is necessary for accurate positioning under gravitational or environmental loads, especially when position sensing is at the motor drives.

When a robot changes its orientation relative to gravity, it will deflect duc to its own weight. Likewise, if a force acts on the arm, it will also deflect. Furthermore, if position sensing is done at the motor drive, this deflection will not be known. Therefore, such deflections must be minimized by increasing stiffness. The stiffness of RAMS arm is about 15 lbs/inch at the tip. This high stiffness is achieved by using high spur gear reductions off the motors, combined with large diameter, short path length stainless steel cables to actuate each joint. The pitch and yaw axes also include an additional 2:1 cable reduction inside the forearm (near the joint) for added stiffness.

7. *Compact/Lightweight*: In some applications, a restricted work-space warrants a small serial manipulator to minimize both geometric and visual interference.

The physical size of the arm is about onc inch in diameter and about 2S cm long. The robot base, containing the motor drives and electrical interfaces, has a 12 cm diameter and is 17.75 cm long. The entire unit (arm and base) weighs about 5.5 lbs. All electrical cables connect to the bottom of the base so as to not protrude into the. robot's work-space.

8. *Fine Incremental Motions*: Human dexterity limitations constrain surgical procedures to feature sizes of about 50-to-100 microns. This arm is designed to achieve 10 microns relative positioning.

By combining many of the features mentioned above (low backlash, low stiction, high stiffness, etc.), this arm is designed to make very small incremental movements. This means that the manipulator can make incremental steps of 10 microns. Note conversely this dots not necessarily mean that the arJn is repeatable to within 10 microns absolute position accuracy.

9. *Tool Wiring Provisions: Some* tools require electrical or pneumatic power which can be routed through the arm in some cases.

The arm is designed to allow running a limited amount of wiring or hoses from the base to the arm's tip (where the tool is mounted). This passageway is about .35 cm in diameter through the wrist and exits through the center of the tooling plate. The wiring can be passed out the base of the robot so that it dots not interfere with its work-space -- as would be the case if such wiring was routed externally.

* "

Electronics and Servo-Control System

1, *Configuration management and control electronics*: *It is necessary* to sense, monitor, and control basic failure conditions (e.g., to implement corrective motion control/braking actions)

A Programmable Logic Device (PLD) controls power and braking relays through an optically isolated interface, and allows fault detection and error recovery. Feature.s of this system arc:

- power up and down button
- manual start-stop buttons to switch motor power from a brake mode to control mode
- panic button to stop motors
- amplifier fuse fault detection
- brake relay fault detection
- watchdog timer fault detection to insure control processors are functioning
- amplifier power supply fault detection
- amplifier fuse fault detection
- PLD logic fault detection.

2. *Commercially available components*: All components of the servo-control system are commercial items avai lable off-the-shelf from vendors with reliable product support.

Use of commercial products and industry standard interfaces in both the servo-contro] system and computing archit ect urc was critical to rapid protot yping *(The development of the robot electromechanical design, electronics, control & computing, followed by a first integration-test-debug-demo nstration was done in less than nine months).* In particular, rapid vendor product support allowed us to quickl y overcome hardware failures and reduce software development cycles by comparison to our past experiences in custom robot computing design & implementation.

RAMS ROBOT COMPUTING AND CONTROLS

System Organization

Figure 2, next page, sketches the RAMS computing and control hardware organization. The major hardware implementation features are as follows: the graphics user interface (GUI) software resides on a UNIX workstation, which also serves as host to a VxWorks real-time control environment. The VxWorks-based control functions arc in turn implemented on a MC 68040 board installed in a VME chassis. A Delta Tau Data Systems PMAC board, also on the VME chassis, controls the six axes of the robot by directly reading the robot sensor outputs and driving the motors through ampl ifiers.

Graphics User Interface

The GUI is based on the X Windows and OSF/Motif librar its. We have developed a number of demonstration modes within the GUI to show and evaluate the capabilities of the robot. These modes arc:

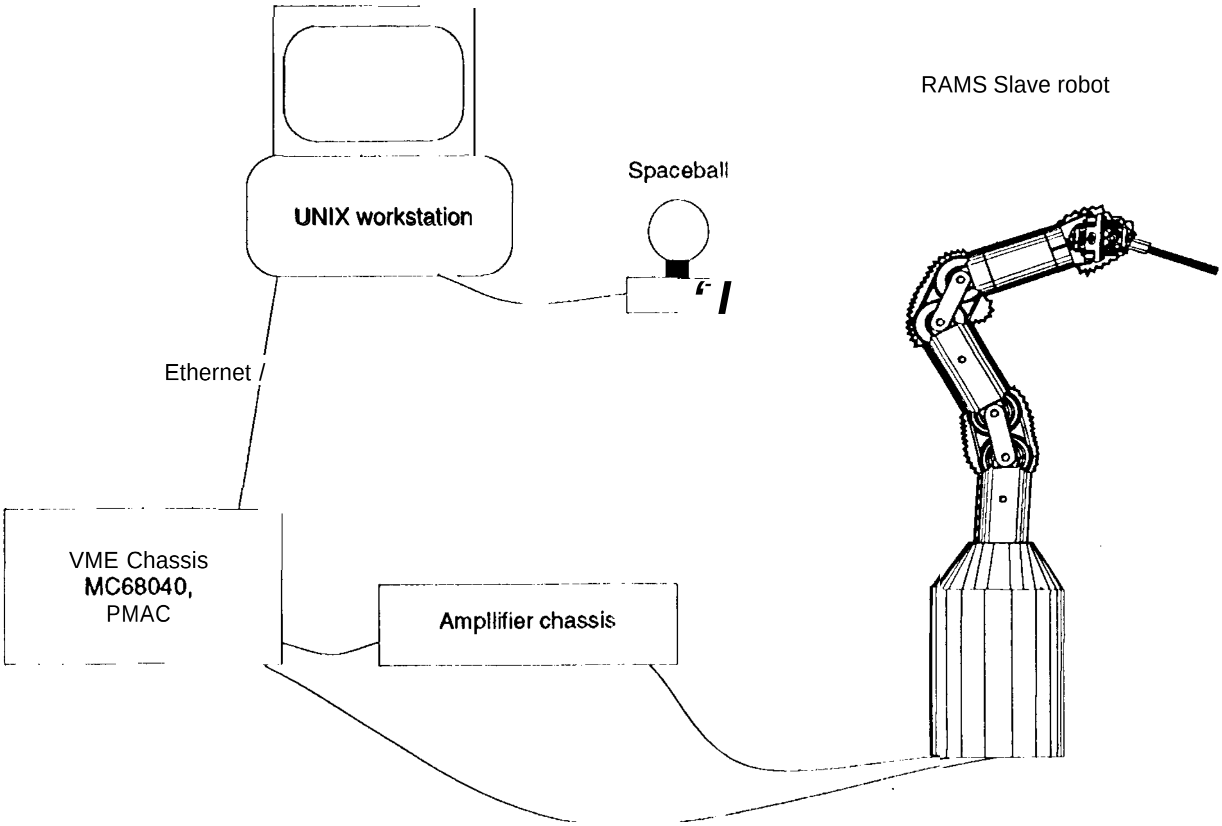


Figure 2: RAMS system hardware organization

(cent 'd.)

- a *manual joint control mode wherein* the user moves individual joints manually by selecting buttons in a control window, incrementing and decrementing a desired joint position
- an *autonomous joint control mode* demonstrating the workspace of the robot. In this mode, the robot simultaneously moves each of its joints in a sinusoidal motion between set limits
- a *manual teleoperated mode* in which the robot is controlled either by using a mouse (or by selecting buttons on a display), incrementing or decrementing motion along single axes of a world-referenced coordinate frame, or by using the spaceball input device to simultaneously move all six axes of the robot
- an *autonomous world space control mode* in which the robot moves its end effector in a sinusoidal motion about one or more Qrtcsian-defined axes simultaneously.

Kinematic and Joint Control

The control software of the robot resides on the VME-based system. **Figure 3** sketches the control flow for the manual and autonomous world coordinate frame-referenced control modes. The general scheme by which the operator currently commands forward control to the robot is as follows: he inputs to the system from the GUI and this input is passed forward using the UNIX socket facility over the Ethernet link. Data thus passed into the control system is specified as desired changes in the robot tip position. We relate these world frame tip coordinate changes to commanded robot joint motions through a Jacobian inverse matrix, which is computed using a JPL-developed Spatial Operator Algebra [14, 15]; this inverse is then multiplied with the input tip displacement vector to determine a corresponding joint position change vector. The primary advantage afforded by the Spatial Operator Algebra for this application is its concise recursive formulation of the kinematics equations, allowing rapid software development and testing -- a simple addition of the joint position change vector to the actual position of the joints results in the desired joint positions for the robot. The desired joint positions are then downloaded to the PMAC controller board wherein joint servo control is performed using a PID loop for each joint axis. In the manual and autonomous joint control modes, the PMAC controller correspondingly receives the joint position change vector as its input. The vector is added to the actual joint positions of the robot and the resulting vector is the desired joint position vector sent to the servo controller.

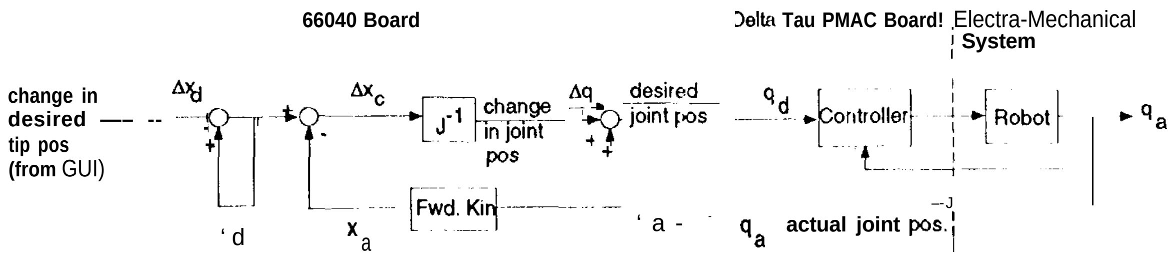


Figure 3: RAMS control flow diagram

RESULTS AND FUTURE PLANS

As of August, 1994, we had integrated the slave robot system described above and demonstrated its successful operation in all control modes. On initial integration, without benefit of significant mechanical tuning or refitting of the robot mechanisms, we achieved repeatable relative positioning of the robot tip to 25 microns or less. This measurement, verified in a number of calibrated and videotaped [16] experiments, was performed both mechanically and optically. in the former case, we utilized calibrated mechanical dial indicators on three orthogonal axes of a wrist-tip-mounted needle; for the latter, we utilized a calibrated viewing field microscope with integrated CCD camera, and programmed and visually monitored a number of different free space, small motions within a 800 micron full-extent reticle, Cumulatively, we observed that both small (micron) and large (centimeter) free space motion trajectories are smooth. Impromptu tests in which a leading microsurgeon compared his free hand motions with that of the robot indicate that the desired scaling will be possible and highly beneficial, given an appropriate hand master interface. Development of such a non-replica master is one immediate project focus, as is also continuing, more quantitative evaluation of the robot, including its loaded (contact) motion performance. Another planned activity is development of control compensation techniques to reject feed-forward "(disturbances" arising from the surgeon's involuntary tremor anti jerk.

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